

A New Two-Dimensional Quantization Method for Digital Image Watermarking

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Abstract— We propose a new technique of Distortion Compensation (DC) for the two dimensional Quincunx Lattice Quantization that is used in watermarking. The choice of a new direction of quantization is explained by the form of Voronoi cell of the lattice elements. Parameter α controls DC and can be adjusted to maximize the mutual information between embedded and detected message in a noisy channel. For a special case of initial distribution of original samples, quantization distortion is estimated and expressed analytically. Experimental evaluation of robustness under Additive White Gaussian Noise (AWGN) is conducted using natural images and compared with several other known two-dimensional Lattice as well as Scalar Quantization methods with conventional DC. Criterion of Watermark to Noise Ratio (WNR) was used for comparison. Among the most important findings related to the Modified Quincunx are: manipulating only a half of samples required in contrast to the other two-dimensional methods; considerably increased mutual information under low WNR; identical to the conventional Quincunx procedure of watermark extraction (decoding).

Keywords— watermarking, quantization, lattice, quincunx.

I. INTRODUCTION

In telecommunication networks, ownership rights protection is one of the most important aspects of multimedia usage. Many approaches applicable to Digital Image Watermarking (DIW) have been developed for the last several decades [1]. The main characteristic for a method in DIW is a trade-off between watermarking distortion and robustness to a specific attack. Image transform and watermark encoding technique are the most important factors that define the mentioned trade-off under a specific attack.

The choice of a suitable image transform is dictated by the definition of watermarking distortion and the kind of attack. Degradation of image quality can be measured according to Peak Signal to Noise Ratio (PSNR), Human Visual System (HVS) etc. [2]. The selection of the measure can rely on the intended application of the watermarked image, availability of the original, computational complexity etc. For example, watermarking in the domain of Singular Value Decomposition (SVD) is considered to have less noticeable impact in comparison with image spatial domain for the same PSNR limit [3].

Large variety of possible attacks can be considered in DIW. Among them there are additive or multiplicative kinds of noise, lossy compression techniques, gamma-correction, geometric manipulation, etc. [4] [5]. Some transforms might be suitable even for cases with multiple attacks scenarios. For instance, in case of JPEG-compression attack as well as

additive noise, watermarking in the domain of Discrete Cosine Transform (DCT) might provide a sufficient robustness [6].

Encoding is another important stage of watermarking which implementation depends on relative watermark length, kind of noise, information available to a decoder, computational sources etc. Quantization Index Modulation (QIM) is a popular technique that provides sufficient robustness-distortion rate under AWGN [7]. Distortion Compensated QIM (DC-QIM) is a generalization of QIM that has an additional parameter to optimize the rate [8] [9]. For a better performance, DC-QIM of a higher dimensionality needs to be used and Nested Lattices (NL) is a suitable framework for that [10]. One of the main limitations of NL practical realizations is shape imperfection that implies non-optimal robustness-distortion rate [11]. Trellis Coded Quantization (TCQ) is another successful multidimensional approach [12, 13]. However, efficient ways of applying DC in TCQ case are not known.

In this paper, we propose a new DC technique that improves robustness-distortion rate of the two-dimensional Quincunx Lattice [11]. According to our approach, quantization is allowed only in the direction which is opposite to Maximum Likelihood Error Scenario (MLES). Therefore all the shifts are orthogonal to the closest grid of a fine lattice. Parameter α defines intensity of quantization shifts and its value can be optimized depending on AWGN level. The performance of the Modified Quincunx (MQ) is compared with conventional DC Quincunx as well as with other known two-dimensional lattice quantization methods.

The paper has the following structure. Detailed description of conventional Quincunx scheme with DC as well as the proposed modification is given in Section 2. Section 3 represents the stages of experimental evaluation of the Modified Quincunx and the results for other methods used for comparison. Discussion of characteristics of the proposed method is given in Section 4. The findings are concluded in Section 5.

II. TWO-DIMENSIONAL QUINCUNX QUANTIZATION

Two-dimensional quantization is considered in this paper and symbol $X \in \mathbb{R}^2$ will be used to denote a random variable which domain is the space of pairs of original coefficients of a host. Using the pair (x_1, x_2) we will denote a particular realization of X (random variables x_1 and x_2 are assumed to be independently distributed).

A. Conventional Quincunx Quantization with DC

One of the most popular 2D-quantization approaches is based on Quincunx scheme [11]. A bit is embedded by modifying a pair of samples (x_1, x_2) . Two different coarse lattices $\Lambda_{c,0}$ and $\Lambda_{c,1}$ are used for embedding of either “0” or “1”. For each element of a lattice we consider a square Voronoi cell and use the name “quantization cell” which size is controlled by parameter Δ (Figure 2). Corresponding (overlapping) grids containing the cells are depicted by solid and dashed lines, respectively (Figure 1).

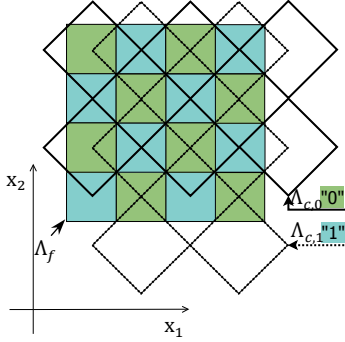


Figure 1. Quincunx lattice quantization and extraction cells for

For all paired original samples in a certain quantization cell the corresponding quantized samples are in the same cell too. For any point in $\mathbb{R}^2$ defined by the pair (x_1, x_2) and labeled with bit b , the center (e.g. lattice element) of the quantization cell that the point belongs to is denoted as (x_1^c, x_2^c) :

$$x_1^c = F_1 + F_2, \quad (1)$$

$$x_2^c = F_1 - F_2, \quad (2)$$

where

$$F_1 = \Delta \left(\left\lfloor \frac{x_1 + x_2}{2\Delta} + 0.5b \right\rfloor - 0.5b + 0.5 \right), \quad (3)$$

$$F_2 = \Delta \left(\left\lfloor \frac{x_1 - x_2}{2\Delta} + 0.5b \right\rfloor - 0.5b + 0.5 \right). \quad (4)$$

The process of quantization according to DC-QIM is represented on Figure 2. Particular realization of quantized random variable $X' \in \mathbb{R}^2$ is denoted as (x'_1, x'_2) . DC-QIM defines (x'_1, x'_2) in the following way:

$$x'_1 = \alpha x_1^c + (1 - \alpha)x_1, \quad (5)$$

$$x'_2 = \alpha x_2^c + (1 - \alpha)x_2, \quad (6)$$

where $\alpha \in [0, 1]$.

Then, watermarked image should be transmitted and the watermark need to be extracted. A grid of fine lattice Λ_f is constructed by smaller square Voronoi cells. The grid is used with the aim to extract information (Figure 1). Here, a half of the cells interpret “0” and the other half interpret “1” (Voronoi regions are filled with green and blue, respectively). For a cell with a particular bit label, we use name “extracting cell” and consider that it is inside the corresponding quantization cell.

An attack (or distortion) may occur during transmission. Therefore, for an extracted bit we use notation $\hat{b}$ instead of notation b that was used for embedding. Therefore, the hard decision detector that we use is given as:

$$\hat{b} = 1 - \text{mod} \left(\left\lceil \frac{x'_1}{\Delta} - 0.5 \right\rceil + \left\lceil \frac{x'_2}{\Delta} - 0.5 \right\rceil, 2 \right). \quad (7)$$

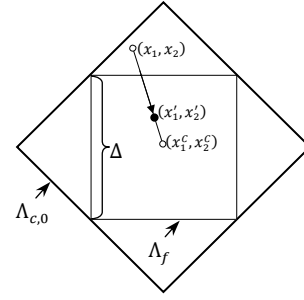


Figure 2. Conventional DC Quantization

The optimality (under AWGN) of the detector defined in (7) depends on the distribution of original samples inside quantization cell [8]. However it is the simplest one among known in the literature and provides reasonably good performance under an assumption that the distribution is close to uniform.

Even in case of no attack, in order to assure absolutely correct extraction of a watermark, all the elements (x_1, x_2) need to be placed inside the corresponding extraction cell. However, from Figure 2 it is clear that the quantization shift in general is not orthogonal to the closest boundary of the extraction cell.

B. Modified Quincunx Quantization with DC

The proposed idea of modification of 2D Quincunx can be explained using MLES concept. Under AWGN, a possible bit error is the result of the shift $(x'_1, x'_2) \xrightarrow{\text{AWGN}} (\hat{x}'_1, \hat{x}'_2)$ that can be directed randomly. Nevertheless, the smallest shift required to produce an error is the one directed normally to the nearest grid of Λ_f . According to AWGN model, the smallest possible shift has the highest probability and we use definition of MLES for that particular error case. Hence, for each particular pair of (x_1, x_2) , quantization in the direction opposite to MLES reduces probability of MLES with the minimal quantization distortion (Figure 3).

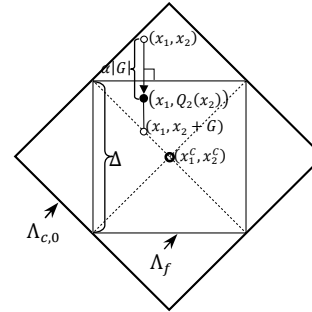


Figure 3. New MLES-based DC

As it can be seen from Figure 3, the shift is orthogonal to the nearest boundary of extraction cell and in case $\alpha = 1$ element (x'_1, x'_2) reaches diagonal of the cell (not the center as the contrast to conventional DC-QIM). Elements that reach a diagonal can not be moved further. Otherwise, in order to counteract MLES efficiently, those elements would need to be moved along the diagonal toward the center. The quantization shift is denoted as G :

$$G = |x_1 - x_1^c| - |x_2 - x_2^c|. \quad (8)$$

Coordinates of a quantized element are defined as

$$(x'_1, x'_2) = \begin{cases} (x_1, x_2), & \text{if } G = 0; \\ (x_1, Q_2(x_2)), & \text{if } G < 0; \\ (Q_1(x_1), x_2), & \text{otherwise;} \end{cases} \quad (9)$$

where

$$Q_1(x_1) = x_1 - \alpha[\text{sign}(x_1 - x_1^c)]G, \quad (10)$$

$$Q_2(x_2) = x_2 + \alpha[\text{sign}(x_2 - x_2^c)]G. \quad (11)$$

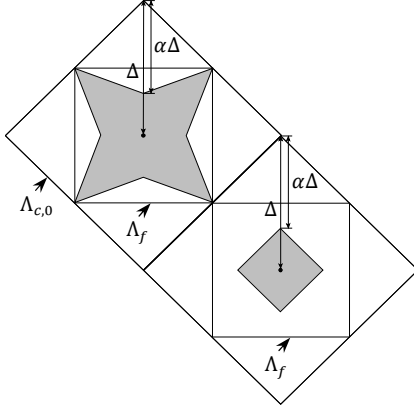


Figure 4. Distribution of quantized samples for MQ (top) and Conventional Quincunx (bottom)

Forms of distribution of samples quantized according to MQ and Conventional Quincunx can be compared on Figure 4 top and bottom quantization cells, respectively.

C. Watermarking Properties of Modified Quincunx

The steps of watermarking procedure are:

- apply a transform to the original image I and obtain a sequence of coefficients $\mathbf{x}$;
- choose (and synchronize with the receiver) a watermarking key K ;
- using K , select pairs $\{(x_1, x_2)^1, (x_1, x_2)^2, \dots, (x_1, x_2)^N\}$ of coefficients;
- obtain pairs of quantized coefficients $\{(x'_1, x'_2)^1, (x'_1, x'_2)^2, \dots, (x'_1, x'_2)^N\}$ according to (9);
- replace original coefficients by corresponding coefficients from $\{(x'_1, x'_2)^1, (x'_1, x'_2)^2, \dots, (x'_1, x'_2)^N\}$ in accordance to K and obtain $\mathbf{x}'$;
- apply the reverse transform to $\mathbf{x}'$ which will result in a watermarked image I' .

One of the most important characteristics for any watermarking method is embedding distortions. For the estimation of the distortions induced by the proposed quantization we assume that Δ is small enough to consider that the distribution of $\mathbf{x}$ inside any quantization cell is uniform. Important difference of the proposed approach compared to DC-QIM is that only one sample out of (x_1, x_2) is being modified. The estimate of quantization distortions is denoted as D and according to (10-11) should be expressed as

$$D = E((x_1 - Q_1(x_1))^2) = E((x_2 - Q_2(x_2))^2) = \alpha^2 E(G^2). \quad (12)$$

Referring to (8), the term $E(G^2)$ can be rewritten as

$$E(G^2) = E((x_1 - x_1^c)^2) + E((x_2 - x_2^c)^2) - 2E(|(x_1 - x_1^c)(x_2 - x_2^c)|). \quad (13)$$

The form of quantization cell is symmetric and therefore

$$E((x_1 - x_1^c)^2) = E((x_2 - x_2^c)^2). \quad (14)$$

Also, appealing to the symmetry we can calculate all the estimates from, for example, the first quadrant of the quantization cell. Quantization distortion in II, III and IV quadrants are the same. The following holds in the I-st quadrant

$$E(|(x_1 - x_1^c)(x_2 - x_2^c)|) = E((x_1 - x_1^c)(x_2 - x_2^c)). \quad (15)$$

Now, let us calculate (14) and (15). For simplicity we replace $x_1 - x_1^c$ with ϵ_1 (also, $x_2 - x_2^c = \epsilon_2$). Because we consider only the first quadrant, parameters ϵ_1, ϵ_2 expressing quantization noise are positive there. We derive that marginal pdf

$$f(\epsilon_1) = \int_0^{\Delta - \epsilon_1} f(\epsilon_1, \epsilon_2) d\epsilon_2, \quad (16)$$

where constant joint pdf $f(\epsilon_1, \epsilon_2)$ is defined as

$$f(\epsilon_1, \epsilon_2) = \frac{1}{\rho}, \quad \rho = \int_0^\Delta d\epsilon_1 \int_0^{\Delta - \epsilon_1} d\epsilon_2 = \frac{\Delta^2}{2}. \quad (17)$$

Hence,

$$E(\epsilon_1^2) = \int_0^\Delta \epsilon_1^2 f(\epsilon_1) d\epsilon_1 = \frac{1}{\rho} \int_0^\Delta \epsilon_1^2 d\epsilon_1 \int_0^{\Delta - \epsilon_1} d\epsilon_2 = \frac{\Delta^4}{12\rho}. \quad (18)$$

Next,

$$E(\epsilon_1 \epsilon_2) = \int_0^\Delta \int_0^{\Delta - \epsilon_1} \epsilon_1 \epsilon_2 f(\epsilon_1, \epsilon_2) d\epsilon_2 d\epsilon_1 = \frac{1}{\rho} \int_0^\Delta \epsilon_1 d\epsilon_1 \int_0^{\Delta - \epsilon_1} \epsilon_2 d\epsilon_2 = \frac{\Delta^4}{24\rho}. \quad (19)$$

And, finally we calculate D according to (13) and substitute the estimate for ρ :

$$D = 2\alpha^2 [E(\epsilon_1^2) - E(\epsilon_1 \epsilon_2)] = \alpha^2 \frac{\Delta^2}{6}. \quad (20)$$

Calculated distortion D for the proposed quantization method can be compared with other known scalar and 2D quantization methods mentioned in [9, 11] (Table 1). From Table 1 it can be seen that for the same pair (α, Δ) the proposed approach provides the smallest embedding distortion.

TABLE 1. QUANTIZATION DISTORTION ESTIMATES. DISTRIBUTION OF ORIGINAL SAMPLES IS UNIFORM

Quantization Method	Distortion
DC-QIM Scalar (1 bit/1 sample)	$\alpha^2 \frac{\Delta^2}{3}$
DC-QIM Quincunx (1 bit/2 samples)	$\alpha^2 \frac{\Delta^2}{3}$
Modified Quincunx (1 bit/2 samples)	$\alpha^2 \frac{\Delta^2}{6}$
DC-QIM Hexagonal #1 (1 trit/2 samples)	$\alpha^2 \frac{5\Delta^2}{12}$
DC-QIM Hexagonal #2 (2 bit/2 samples)	$\alpha^2 \frac{5\Delta^2}{9}$

The watermarked image I' should be transmitted via some channel where an attack might occur. Therefore, the receiver has access to possibly distorted watermarked image $\hat{I}'$ that he/she needs to extract the watermark from. The steps of extracting procedure are:

- apply a transform to the distorted image $\hat{I}'$ and obtain a sequence of coefficients $\hat{\mathbf{x}}'$;

- using K , select pairs $\{(\hat{x}'_1, \hat{x}'_2)^1, (\hat{x}'_1, \hat{x}'_2)^2, \dots, (\hat{x}'_1, \hat{x}'_2)^N\}$ of coefficients;
- from each pair $(\hat{x}'_1, \hat{x}'_2)^i$ extract a watermark bit $\hat{b}^i$ according to (7).

It is important that the procedure of watermark extraction for the proposed MQ scheme is the same as in the case with conventional DC-QIM Quincunx. Hence, any of the Quincunx embedding schemes can be used (without notifying the receiver) which increases the efficiency of watermarking under different types of distortions.

III. EXPERIMENTAL EVALUATION OF THE METHOD

In this section we experimentally evaluate robustness of the proposed quantization scheme. Further in the text, the term “extracted information” means maximized (over α) mutual information between messages that are embedded and detected using a pair of samples. We use the hard decision detector that is described by equation (7). The robustness is estimated under consideration that AWGN attack is applied to the watermarked data.

The severity of AWGN attack is measured by WNR:

$$WNR = 10 \log_{10} \left(\frac{D}{\sigma^2} \right), \quad (21)$$

where σ^2 is the variance of AWGN. Substituting the expression for D for the MQ we derive that $WNR \approx 20 \log_{10}(\alpha \Delta / \sigma) - 7.782$. The related question of watermarking performance was examined in details in [14]. Simplified settings assuming uniform distribution of original samples inside quantization interval are discussed in [15]. It was shown there that, in scalar quantization case the extracted information depends only on parameters α and Δ / σ . Therefore, during the experiment, for a given pair (WNR, α) the required Δ / σ is calculated as:

$$\Delta / \sigma = \frac{1}{\alpha} 10^{\left(\frac{WNR + 7.782}{20} \right)}. \quad (22)$$

For the purpose of the experiment, 72 natural grayscale images of different resolution were selected. For each image, 8x8 blocks were formed from adjacent pixels and passed to Singular Value Decomposition (SVD) transform. The choice of SVD is due to its popularity and quite moderate visual impact [16]. First singular values were chosen as the coefficients that form $\mathbf{x}$. A key K was used to select pairs $\{(x_1, x_2)^1, (x_1, x_2)^2, \dots, (x_1, x_2)^N\}$ from $\mathbf{x}$. After corresponding grids with quantization cells are formed, uniform and independent 2D distribution inside cells has been confirmed according to the goodness of fit criterion. Therefore, previously derived analytical estimate for quantization distortion D can be considered as precise in the case with natural signal as well.

In order to index WNR correctly, in the domain where the quantization takes place, AWGN attack was applied directly to the set $\mathbf{x}'$ of quantized coefficients (not the composed image I'). Bit Error Rate (BER) was calculated upon extraction of watermark data from $\hat{\mathbf{x}}'$. The diagram of the experimental approbation of the MQ is given on Figure 5.

On the diagram, original pairs of coefficients, quantized, and corrupted by AWGN are denoted as $\mathbf{X}, \mathbf{D}\mathbf{t}, \hat{\mathbf{X}}'$ respectively. Original and extracted watermark data is denoted as $\mathbf{D}\mathbf{t}$ and $\hat{\mathbf{D}}\mathbf{t}$. Procedure of embedding is denoted as Em and requires

$\mathbf{X}, \mathbf{D}\mathbf{t}, \Delta, \alpha$ as arguments. Attack is denoted as $AWGN$ and extraction is Ex .

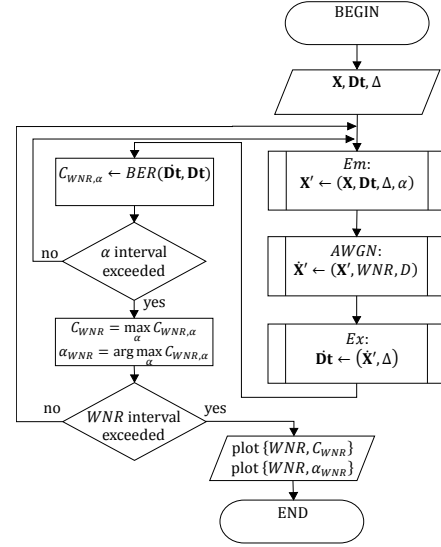


Figure 5. Diagram of the experiment

The final result of all iterations with the same WNR index is α_{WNR} that maximizes extracted information under attack with that WNR value. The whole α -diapason is searched in order to find α_{WNR} for each WNR. The final result of the entire experimental approbation is the plot of the best α_{WNR} values drawn toward WNR (Figure 6).

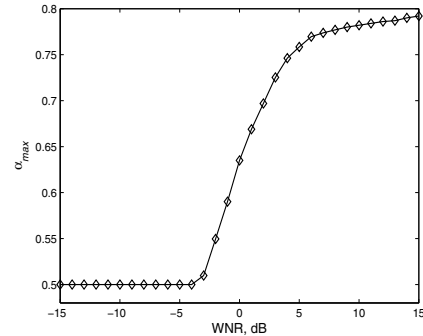


Figure 6. Optimal values for α

It can be seen that optimal α values are increasing with the increase of WNR. It might be not clear on the stage of watermark embedding if the attack will occur in the channel during transmission. Therefore the settings of the experiment were so that in case of no distortion the extracted watermark does not contain errors. For that purpose it is required that $\alpha \geq 0.5$ (Figure 6).

The extracted information plot toward WNR is shown on Figure 7. Extracted information index C has been calculated during the experiment using BER between $\mathbf{D}\mathbf{t}$ and $\hat{\mathbf{D}}\mathbf{t}$:

$$C = 1 + BER \log_2 BER + (1 - BER) \log_2 (1 - BER). \quad (23)$$

Information plots for other popular two-dimensional quantization methods are depicted on Figure 7. Comparing the performance of the MQ with the other known techniques we

can witness considerable advantage of the proposed technique under $WNR \leq -3\text{dB}$.

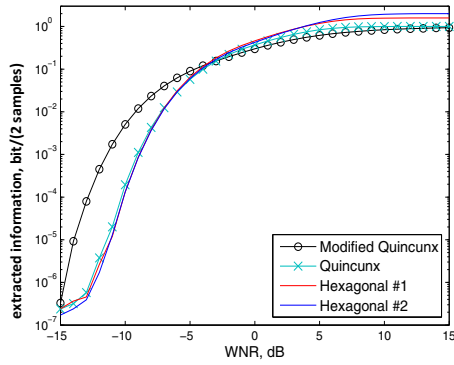


Figure 7. Performance for different Quantization Methods

IV. DISCUSSION

We will discuss in this section some of the most important watermarking characteristics of the Modified Quincunx.

Well-known Quincunx lattice was used which cell form is far from being hyperspherical and, therefore can not be considered optimal for Dither Modulation embedding. Nevertheless new DC technique improves watermarking properties. One of the most vivid advantages of the proposed method can be seen from Figure 7 for low WNRs. On the other hand it is clear that for higher WNRs the method's performance is the worst among the selected methods. Obviously, the explanation to this phenomenon can be found in the form of the distribution of the quantized samples. For instance, in case $\alpha = 0.5$ the distribution of the quantized samples is uniform and is inside extraction cell. Consistency and low quantization distortion make the method efficient under low WNRs. Higher WNRs require larger α . In case $\alpha = 1$, the quantized samples are located only on the diagonals of the extraction cell. The distribution is spread far away from the center which is the main reason for poor performance in contrast to other methods. Luckily, the extraction procedures for the MQ and conventional Quincunx are the same and the advantages of the both methods can be combined. For instance, the solution might be to use MQ for $WNR \leq -3\text{dB}$ and to use Conventional Quincunx for $WNR > -3\text{dB}$.

In some cases, quantization distortion might have a crucial impact on a watermarked image. Fine Art Photography or medical imaging are good examples. In the latter case, a patient might want to assure protection for his/her personal data and limit its misuse or uncontrolled copying and distribution. However, an impact of watermarking can cause quality deterioration which results in incorrect diagnosis and subsequent treatment. In order to avoid this, watermarking energy should be low.

Unfortunately, low-energy watermarking faces some complications in digital images. One of such complications is due to discretization of pixel values of watermarked images [17]. It might cause significant BER for low-energy watermarking even prior any attack in the transmission channel. An evident advantage of the proposed in this paper quantization scheme is that only one sample out of (x_1, x_2) needs to be modified during watermark embedding. Therefore,

only one sample might suffer from discretization. Additionally, the estimate for D for MQ is the lowest in Table 1 which means that there is higher capability to increase Δ compared to other DC-QIM based approaches. The developed technique has been tested in collaboration with medical experts. An image of prostate cancer case (Figure 8) was watermarked with Document to Watermark Ratio (DWR) equal 30dB. According to the final assessment, as a result of a double-blind review, made by medical expert group, the interpreted diagnostic information for original and watermarked images is identical. Hence, the fidelity of the watermarked images can be considered as acceptable for that particular medical application.

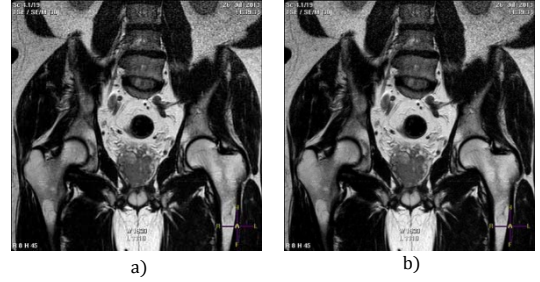


Figure 8. Prostate cancer case: a) Original diagnostic image; b) Watermarked image

For the both MQ and Scalar DC-QIM (SDC-QIM) only one sample needs to be modified to embed 1 bit. We compared the efficiency of the methods SDC-QIM, Quincunx and MQ. With the aim to make comparison more versatile we consider three possible settings for AWGN attack on SDC-QIM. Nevertheless, settings for Quincunx and MQ are the same in each of the comparing scenarios: N -bit watermark is embedded in $2N$ samples and AWGN is applied to the quantized $2N$ samples.

Scenario 1 for SDC-QIM is: N samples are used for watermark embedding and AWGN attack energy is spread on N quantized samples. Scenario 2: N samples are used for watermark embedding but AWGN attack energy is spread on all the $2N$ samples. Scenario 3: the same N -bit watermark is embedded two times in $2N$ samples and AWGN attack energy is spread on all the $2N$ quantized samples. Extracted information vs. WNR plots for all the mentioned cases are shown on Figure 9.

Scenario 2 can be seen as the most beneficial for scalar quantization as in that case SDC-QIM outperforms Quincunx and MQ on all the WNR diapason. However, according to Scenario 2 fraudulent tampering (as a result of an attack) of only N quantized samples out of total $2N$ samples can potentially be detected. As a contrast to that, Quincunx and MQ have potential to detect fraudulent tampering in all the $2N$ samples. This feature can be especially valuable for a number of semi-fragile and fragile watermarking applications where image integrity is important [18] [19] [20].

According to Scenario 3, tampering of all the $2N$ samples can potentially be detected using SDC-QIM. From Figure 9 it can be seen that SDC-QIM outperforms Quincunx on almost all the WNR diapason but performs worse than MQ for $WNR \leq -4\text{dB}$. Finally, SDC-QIM demonstrates the worst performance under Scenario 1 (except $WNR \geq 5\text{dB}$ where it slightly outperforms MQ).

and other members of collaborating oncological expert group from Cyber Clinic Spizhenko, Kiev, Ukraine.

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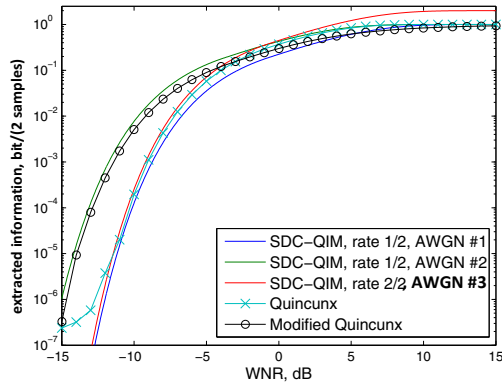


Figure 9. Information plots for Scalar and two-dimensional Quantization Methods

V. CONCLUSIONS

A modified two-dimensional Quincunx-based quantization approach is proposed in this paper. Even though well-known lattice is used, a new Distortion Compensated technique results in a sufficient improvement of watermarking characteristics. In comparison to other two-dimensional approaches Modified Quincunx provides higher extracted information under intense AWGN. The demonstrated improvement is mainly due to using MLES concept that offers a new form for the distribution of quantized samples.

For a given pair of original samples, the direction of the most probable error-causing disturbance is defined according to MLES concept. The proposed DC quantization is performed in the opposite direction in order to reduce probability of MLES. Due to Quincunx-form cells, diagonals serve the natural limit for the quantization which results in a new form of the distribution of quantized samples. Quantization distortion and the form of the distribution depend on parameter α that value has been optimized for different levels of WNR. The procedure of watermark extraction for the Modified and conventional Quincunx is the same that allows interchangeable utilization of the methods without informing the receiver.

The efficiency of the Modified Quincunx has been estimated using natural grayscale images. According to the experimental data, the modification considerably increases extracted information (up to 10^2 times) compared to other 2D quantization methods under low WNRs. Low quantization distortion reduces a negative impact on the perceptual quality which may contribute to a number of possible practical implementations of the method. Additionally, some properties of the method have been discussed and compared with scalar DC-QIM under several possible attack scenarios. Notably, in most cases the modified method is more advantageous than the scalar one.

Our further efforts will be to put forward an improved MLES-based DC quantization technique as well as to increase its dimensionality by utilizing, for instance, the structure of some well-known codes.

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